

Unsteady Hydrodynamics of the Maneuvering Submarine

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Abstract

The development of a parallel, fully unsteady, Reynolds-averaged Navier-Stokes (UnRANS) code for turbulent flow, together with the availability of fast parallel computers able to execute extremely large problems, have for the first time permitted addressing the prediction of maneuvering submarine hydrodynamics without the use of extensive simplifying approximations. One such code, UNCLE, is being utilized and modified to compute the complex flowfield around rotating propulsors, around the hull and appendages, and finally around the complete vehicle, predicting the forces, moments, and the resulting trajectory. This project encompasses the prediction of unsteady, three-dimensional, turbulent flow at high Reynolds number around complex shapes undergoing maneuvers and having components in relative motion. The ultimate objective is the prediction of full six-degree-of-freedom maneuvers and the time history of forces on various components, incorporating operation of internal systems, such as ballasting, and control sequences for the propulsor and control surfaces. The present approach obviates the previous extensive simplifications and approximations to the flow physics and can in principle address high Reynolds number flows directly. The flow solver uses an artificial compressibility formulation for unsteady flow to solve the three-dimensional time-dependent equations in multi-block transformed coordinates. The overall code has been developed in two parts, a propulsor code and a hull/appendage code, which are now integrated. Both the propulsor and hull/appendage versions of the parallel code were validated against experimental data and against previous serial code results. An unstructured version of the code is under development, and progress is summarized. Computations on classified configurations have also been run but are not reported here.

Introduction: The Computational Problem

A variety of computational problems previously inaccessible can now be addressed due to the development of high-speed parallel computers with large memory capacity per node. Unsteady, turbulent, viscous flow at high Reynolds numbers around moving bodies with parts in relative motion could not have been attempted earlier but is now within reach of practical prediction. Such high Reynolds number flow around complex shapes contains an enormous range of length scales and requires high-resolution grids, accurate and stable numerics, turbulence models, and efficient solution per time step. Over the past several years a code has been under development to meet these demands for the important case of the unsteady hydrodynamics of the maneuvering submarine (McDonald and Whitfield, 1996). The prediction of the maneuvering of vehicles and weapons in general must address the flow around components in relative motion, such as control surfaces, as well as the unsteady nature of the flow around the overall body. Forces on the hull, as opposed to lifting surfaces, dominate submarine dynamics, which accentuates the requirement for accuracy in the prediction of three-dimensional separation regions. Also, a large rotating propulsor is an essential component of submarines whose performance must be captured accurately. The complex geometry of the propulsor and its performance in unsteady, nonuniform inflow conditions is a challenging problem

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in its own right, and the unsteady nature of the flow through it in a body-fixed coordinate system is extremely demanding.

This computational project attempts to overcome the limitations of present maneuvering prediction methods which depend on highly empirical approaches, extensive approximations, and model-scale testing which must be scaled in a somewhat ad hoc fashion to the extremely high Reynolds numbers of applications. Of particular interest are severe maneuvers, which are the most challenging to the present methods. The computational solution of the Reynolds-averaged Navier-Stokes equations (RANS) in a fully unsteady (UnRANS) setting can in principle address Reynolds numbers from model scale to full scale. However, to achieve this objective requires efficient and accurate numerics, both in time and space, spatial grids which resolve the important flow features and which accommodate relative motion of components, and turbulence models compatible with the overall solution approach.

Approach

The flow around a powered, maneuvering submarine is highly complex due to the interactions among hull boundary layers, appendage boundary layers and wakes, and the propulsor. Time-dependent trajectories, large angles of attack, and relative motion of components result in a highly unsteady flow. Consequently, the flow fields are represented by the UnRANS equations and solved numerically using the code UNCLE as the primary flow solver both for the overall flow and for the propulsor. This flow solver uses an artificial compressibility formulation to solve the three-dimensional unsteady incompressible equations in multi-block transformed coordinates (Sheng et al., 1997). The parallel implementation uses domain decomposition to partition and map the data space onto a set of processors. Static load balancing is done at the grid generation stage based on a heuristic performance estimator that takes into account the characteristics of the algorithm and the available system resources. The unsteady finite-volume approximation of the governing equations is solved iteratively at each time step using a parallel multigrid/relaxation iteration scheme (Pankajakshan and Briley, 1995). This involves a point-to-point message exchange at each subiteration level. The code uses MPI because of its extensive portability and functionality. The combined propulsor and hull/appendage flow computational routines are embedded in a six-degree-of-freedom (6DOF) dynamic shell to determine at each time step the integrated forces and moments and the resulting change in orientation and trajectory of the vehicle. Future capabilities will include ballast effects, body-force propulsor models, and other features such as flapped control surfaces and near-surface wave forces. Complications in the flowfield include: advanced propulsors such as the turbomachine-like Syrenian concept from MIT (Kirwin et al., 1994); high Reynolds numbers; flow separation at large angles of incidence; and moving control surfaces.

Progress

The most recent efforts have focused on bringing the computational capability close to the intended goal of a useful trajectory prediction tool ready for transfer to application use (Pankajakshan, et al., 2000). This will culminate in FY00 by comparing predictions against actual measurements of the trajectory of a radio-controlled model (RCM) especially designed to provide unclassified data for code validation. Specific progress has been achieved in developing and testing sailplane operation in a rising maneuver, modularizing control-surface code for ease of use, module source access for such code components as the turbulence model and control algorithms, force and moment computation for parts of the vehicle such as control surfaces, and the initiation of an unstructured grid version of the code.

Code modularity is important for a code which will potentially be used for a wide variety of configurations and dynamic conditions. For instance the incorporation of control algorithms may be desired to test their

performance during emergency maneuvers. Ship weight and ballast distribution will need to be incorporated to simulate variable trim conditions. Various turbulence models are likely to be needed as other sources of inaccuracy are eliminated. A modular approach simplifies the modification process and reduces the likelihood of coding errors which may affect the performance of the overall code. Such modularity has been partially implemented in the code at this time, particularly for the turbulence model and control algorithms.

During validation of the code's performance, it may be desirable to investigate the forces and moments on various components of the platform such as the sail or control surfaces. This may also be desirable during platform design in order to select components from among a range of possible configurations. The capability to do this within the code has been incorporated for the types of components presently addressed.

A common control surface configuration on many submarines includes rise/dive planes on the sail (sailplanes). Because of the curving surface of the sail joining to the rotating sailplane, a fixed portion of the sailplane, termed a pedestal, is required together with a gap between it and the remainder of the sailplane. Such a configuration has been gridded and run for a rising maneuver as shown in Fig. 1. Though run for only a notional submarine configuration, it demonstrated the expected characteristics of such a maneuver. This solution had 4.5 million points (4.5 Gb), and each hull length traveled (2260 steps) required 55 hours on 50 processors, using a Cray T3E.

Preparation is underway for the computation of the RCM (Fig. 2) maneuvers conducted for validation of the code performance. A variety of maneuvers were performed, including repeat runs to quantify variability, some of which will be used for preliminary testing and some for blind comparisons with the computations. These comparisons will be the first quantitative tests of unsteady RANS performance for a maneuvering vehicle.

In performing maneuvering simulations, grid generation for structured grids becomes increasingly difficult for very complex geometries, and the number of grid points (and runtime) increases due to unavoidable over-resolution in some regions because of structured grid topology. Accordingly, a maneuvering capability that uses unstructured grids has been initiated. The unstructured capability is being demonstrated and validated by recomputing cases previously run with structured grids, an approach successfully used to accelerate development of a scalable parallel version of the sequential submarine code in past years.

Considerable progress in the unstructured grid code has been made in the past year. A q-omega turbulence model has been incorporated, and a capability for rotating propulsors has been implemented. The 6DOF code has also been incorporated into the unstructured code. The unstructured code now has most of the operational capabilities of the structured code except for moving control surfaces and free surface hydrodynamics. A validation of force and moment predictions for the appended SUBOFF (notional submarine) hull for a range of incidence angles has been completed using the unstructured solver, and the computed results agree very well with measurements for axial and normal forces (Fig. 3, 4) and pitching moments. A straight-ahead solution for the full configuration SUBOFF with rotating propulsor has also been computed for both model-scale (1.4×10^7) and full-scale (10^9) Reynolds numbers, Fig. 5. These results are currently being evaluated. The model-scale solution had 7.8 million points (16 Gb) and required 34 hours per prop revolution (240 steps) on 48 processors (Sun Enterprise 10000). The full-scale solution had 10.75 million points (23 Gb) and required 40 hours per revolution on 62 processors. Both solutions had sublayer resolutions less than $y^+ = 1$ at all surface points.

Summary

Significant advances in both structured and unstructured code development and implementation have been achieved toward computation of the trajectory of a propelled, controlled, maneuvering submarine. The structured code has progressed to the point where validation of the predictions may be undertaken. This is underway for an unclassified radio-controlled submarine model and will be completed during this year. A variety of extensions to the code capability have been implemented including sailplane motion, code modularity for ease of revision, and separate computation of forces and moments on components. The unstructured version holds promise for greatly reduced gridding time, the primary bottleneck in application of CFD. It has been employed for initial computations of a full-scale notional submarine and converged to a qualitatively reasonable state. The final phase of validation will address emergency recoveries and other extreme maneuvers.

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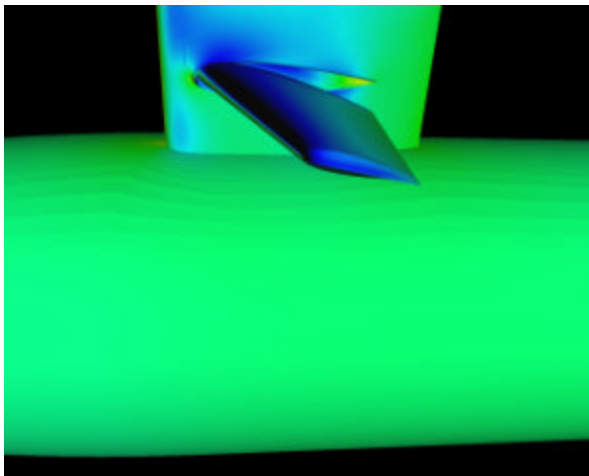


Figure 1. Sailplane for rise maneuver.

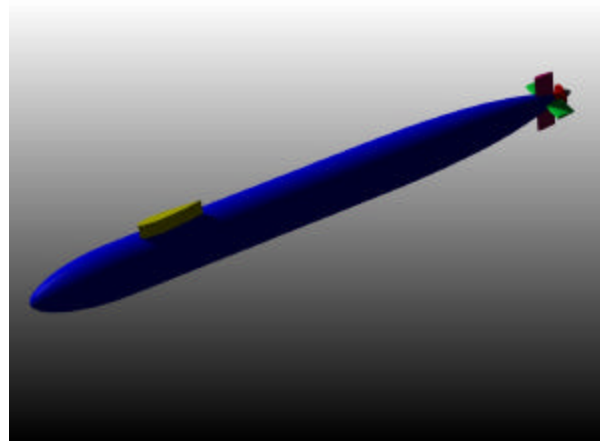


Figure 2. Radio-controlled model for validation experiments.

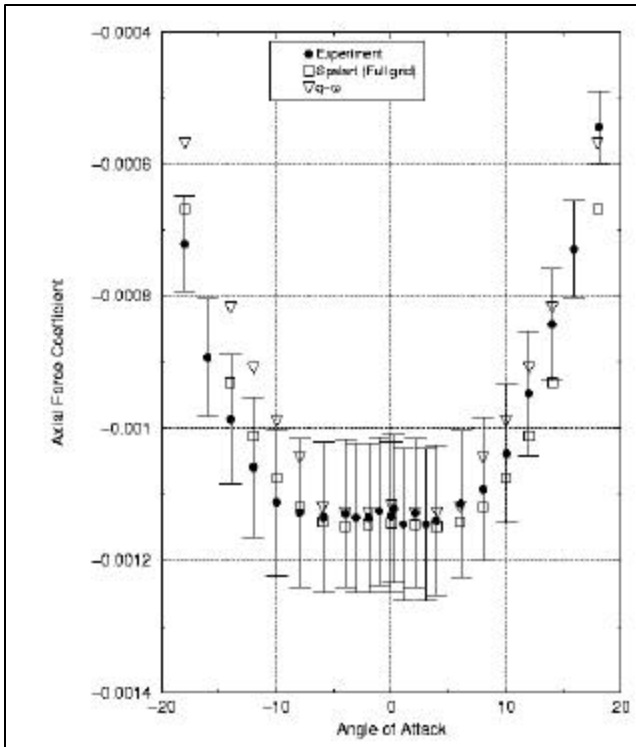


Figure 3. Axial force computation and experiment.

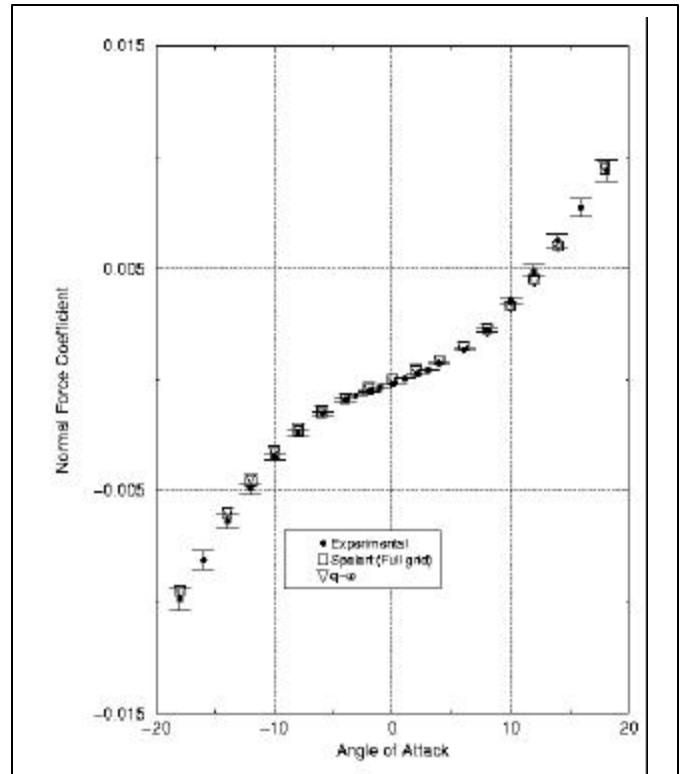


Figure 4. Normal force computation and experiment.

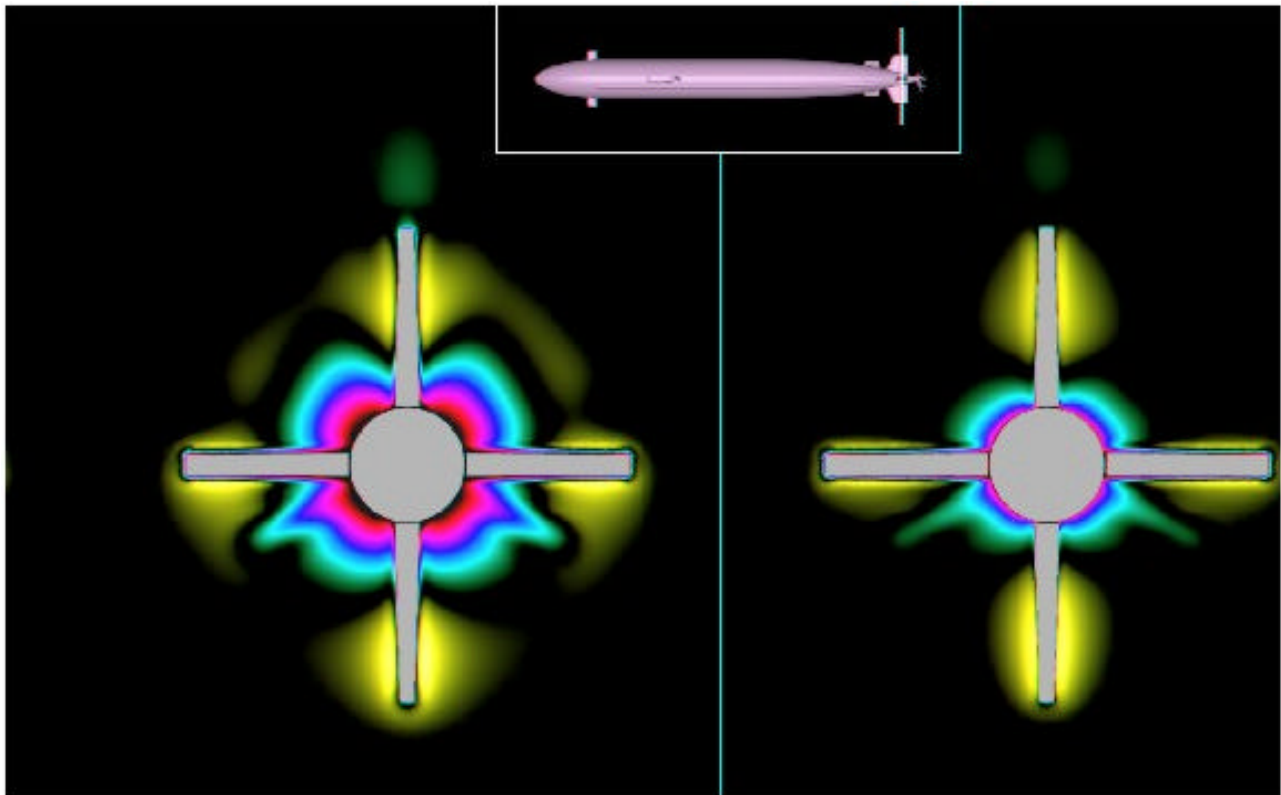


Figure 5. Axial flow in stern region of notional submarine at model-scale (1.4×10^7) and full-scale (10^9) Reynolds number. Model-scale solution is to the left, and full-scale is to the right.